ANGLE OF INCIDENCE CORRECTIONS FOR GaAs/Ge SOLAR CELLS WITH LOW ABSORPTANCE COVERGLASS

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ABSTRACT

A total of four different types of coverglass/filter combinations were tested over a O to 85 degree angle of incidence range. One group of cells was irradiated to provide additional data, A predicted cell response was calculated using the cosine and Fresnel corrections. A comparison of measured versus predicted values showed a good fit for blue reflection or anti-reflection (AR) filters. Both blue-red and infrared reflection filtered cells showed decreased output in the 40 to 80 degree range due to movement of filter IR band-edge into cell response range. Performance at very high incidence angles is still not fully understood. A special infrared filter was used which did not have an angle of incidence effect. Irradiation of cells had little or no effect on angle of incidence performance.

INTRODUCTION

The Jet Propulsion Laboratory Mars Pathfinder mission has three different solar arrays each of which sees changes in incidence angle during normal operation. When solar array angle of incidence effects were researched, little published data was found [1-4]. The literature only documented the cosine and the Fresnel reflection corrections for angle of incidence but did mention other possible factors. MEASAT, a spinning spacecraft made by Hughes Space and Communications Company (HSC), has the world's first commercial spacecraft gallium arsenide on germanium solar array. This solar array uses infrared reflection filters to lower army operating temperatures. Angle of incidence effects on the MEASAT were of interest and were measured at JPL. This data satisfied the needs of both the JPL and the Hughes spacecraft programs.

DATA Collection

LAPSS

The Large Area Pulsed Solar simulator (LAPSS) is a research tool at JPL and was used for creating and collecting all of the data in this paper. The LAPSS has been described in detail elsewhere [5] and thus will not be described here.

cells

Angle of incidence measurements were made on the cells by attaching them to a divider head which was carefully aligned normal to the light beam at O angle of incidence. The cells were run with identical incidence angles both left and right of normal which allowed a consistency as well as a normality check.

The HSCC 3.46 cm by 6.91 cm gallium arsenide on germanium (GaAs/Ge) cells were all made by Spectrolab. Details of the cell coverglass/filter assemblies used for the angle of incidence measurements areas follows

a. GaAs/Ge (281, 282) which had Optical Coatings Laboratory Incorporated (OCLI) blue-red reflection (BRR) filters on 3-mil ceria-doped Coming 0213 microsheet coverglasses;

b. GaAs/Ge (60, 85,91, 93) which had Pilkington Space Technology (PST) infra-red reflection (IRR) filters on 3-mil ceria-doped CMX coverglasses;

c. GaAs/Ge (77, 79, 83, 88) which had PST IRR filters on 3-mil ceria-doped CMX coverglasses and had been irradiated with 2.5 x 10'^4 Mev electrons;

d. GaAsGe(103) which had special PST IRR filter on 3-mil ceria-doped CMX coverglass which was optimized to reduce angle of incidence effects.

e. Silicon (C005) which was used as a control and was an old Spectrolab K-6 type cell with a 30-mil quartz coverglass and a 350 nm blue reflection filter.

THEORY

Before data reduction and analysis was attempted, a number of potential angle of incidence dependent effects were examined.

Cosine - The cosine correction is due to the change in effective array collection area due to the projection of the off-normal array surface onto a plane normal to incident light.

Fresnel Reflectivity - Fresnel reflection is due to the interface between two optical media having different indices of refraction. The reflected portion of the incident light is given by:

$$r = \frac{1}{2}\left[\frac{\tan^2(\phi_1 - \phi_2)}{\tan^2(\phi_1 + \phi_2)} + \frac{\sin^2(\phi_1 - \phi_2)}{\sin^2(\phi_1 + \phi_2)}\right]$$

where ϕ_1 is the incident beam angle and&is the refracted beam angle. Since only the light reaching the cell was of interest a correction was made for the small reflection loss at normal incidence (i.e. 1.770).

Coatings and Filters - Low absorptance filters, such as BRR or IRR, on the coverglass or the cell front surface are likely to cause a decrease in cell response at off-normal angles due to movement of the in W band edge into the cell response wavelengths.

Multi-Layer Problem - There may be some additional effects from multiple surface reflections or multi-layer coatings [6].

Extreme Angle Effects - Light trapping or cell shadowing may happen when very large incidence angles are encountered. These effects are difficult to quantify but have been reported [3].

Low Intensity Effects

Temperature - A decrease in temperature is normal when the angle of incidence increases for a solar array exposed to constant sunlight. The pulsed light source of the LAPSS does not create any temperature effects so this factor could be ignored.

Voltage - Lower intensities due to angle of incidence do result in lower cell voltages. This study however focussed upon the short circuit current and thus did not correct for this effect.

DATA ANALYSIS

Index of Refraction

The front surface of most coverglasses was coated with magnesium fluoride (MgF_2) which is common practice. The OCLI BRR coverglasses had a UVR coating on the front instead of MgF_2. A published material value of 1.38 for the front surface index of refraction was first used for the Fresnel reflection calculation but later a better fit (i.e. less total deviation) between actual and **predicted values was** found by using an index of refraction of 1.35.

Deviation from **Cosine** Factor

To quantify the angle of incidence effects in a manner which is useful to solar array designers, it is convenient to define a "deviation from cosine factor". This factor is useful for applications, such as spinning arrays, where all angles of incidence are important. The factor may be defined for both I_{sc} and I_{mp} as follows:

$$F(I_x) = \frac{\int I_x(\theta) \cdot d\theta}{I_x(\theta = 0)\int (\cos\theta) \cdot d\theta}$$

where x is sc (short circuit), sv (specific voltage), or mp (maximum power); F is deviation from cosine factor; and I_x is measured current or voltage of solar cell illuminated at angle of incidence Θ. The integral is taken over the range of angles of interest. The calculated deviation from cosine factor for each test cell, integrated from -90° to +90°, is shown in Table 1. As seen in the table, both the IRR and BRR show approximately 2?40 more current loss than the silicon control cell. However, the irradiated IRR cell shows only 1 % more loss. The cell with the custom IRR, designed to mitigate the deviation from cosine factor, has nearfy the same performance as the silicon control and the AR only cells. Cell Filters

There were three different types of coverglass filters BRR reflection filters made by OCLI; IRR reflection filters made by PST; and **a 350 nm blue reflection filter on** fused quartz for the control cell.

ANGLE OF INCIDENCE EFFECT OF FILTERS

The silicon control cell which only had a blue reflection filter and the cell with the special IRR filter by PST exhibited predicted angle of incidence effects (See Figure 1).

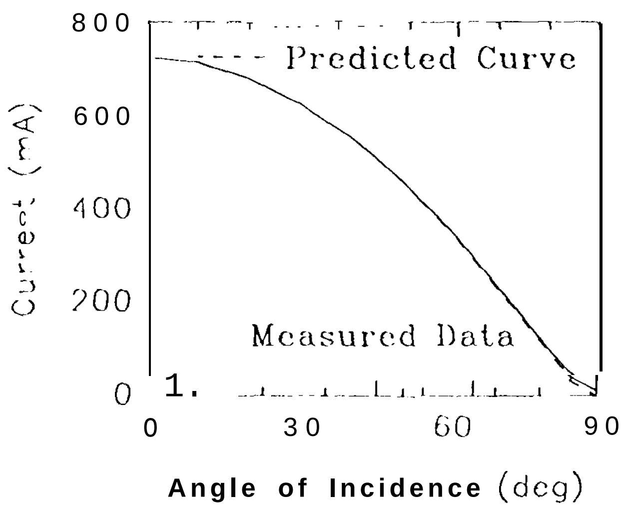

Figure 1 - Response of Cells with AR or Blue Reflection Filters

The calls with BRR and IRR filters showed a significant **deviation** of measured values below predicted values in the middle ranges of 40 through 80 degrees. See Figure 2.

Table 1. Deviation From Cosine Values

Cell Serial Number	Coverglass Type	Cell Type	$F(I_{sc})$	$F(I_{mp})$
C005	Fused silica	Silicon K6	0.972	0.976
150	AR/0213	GaAs/Ge	0.979	0.975
157	AR/0213	GaAs/Ge	0.977	0.974
209	AR/CMG	GaAs/Ge	0.983	0.977
228	AR/CMG	GaAs/Ge	0.983	0.981
Average AR	AR	GaAs/Ge	0.981	0.977
281	BRR	GaAs/Ge	0.959	0.956
282	BRR	GaAs/Ge	0.963	0.960
Average BRR	BRR	GaAs/Ge	0.960	0.956
80	IRR	GaAs/Ge	0.949	0.945
85	IRR	GaAs/Ge	0.957	0.954
91	IRR	GaAs/Ge	0.954	0.951
9 3	IRR	GaAs/Ge	0.956	0.952
Average IRR	IRR	GaAs/Ge	O w l	0.951
77	irradiated IRR	irrad. GaAs/Ge	0.963	0.958
79	irradiated IRR	irrad. GaAs/Ge	0.972	0.971
83	irradiated IRR	irrad. GaAs/Ge	0.964	0.933
88	irradiated IRR	irrad. GaAs/Ge	0$60	0.956
Av. rad IRR	irradiated IRR	in-act. GaAs/Ge	0.%5	0.%2
103	custom IRR	GaAs/Ge	0.974	0.971

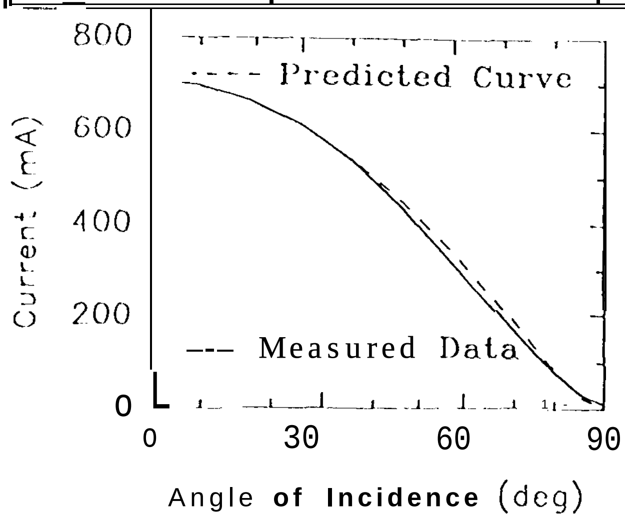

Figure 2- Response of Cells with BRR and IRR Filters

Movement of the filter band edge was mentioned the theory section and is assumed hereto be correct.

An unexpected deviation of the Voc from the usual log(Isc) relationship was noted, This deviation was seen in some GaAs/Ge cells but not in others nor in the silicon control cell. After testing the same cells at various reduced intensity levels by using slit filters and non-ml incidence light, it was found that this deviation was not angle of incidence dependent so this was not pursue.

Special Filters

PST developed for HSC a special IRR filter to minimize performance drop due to angle of incidence effects. Cells with these filters reduce the angle of incidence effects by **centering the** infrared reflectance band at longer wavelengths. This approach causes a cell absorptance higher than with a standard IRR filter.

Radiation Effects

It was interesting to note that the irradiated cells had less deviation from predicted values than the similar non-irradiated cells.

Extreme Angle Effects

Extreme angle effects at 85 degrees were noted with measured values significantly higher than predicted values. It is highly probable that there is **an edge effect due to light trapping** however, a more detailed search is required to fully answer this question.

ERRORS

Systematic

There are three different systematic error causes: large incidence angles, reduced reading size, and assumed index of refraction.

Large Incidence Angles - The cosine value changes rapidly at large incidence angles so small angle errors become a concern. Alignment of cell sample to light beam was carefully done but the source is 35 feet away from the sample and there is no hard-mounted goniometer to use as a reference. Stray room light and wall reflection become larger percentage effects as the incidence angle increases. This effect was minimized by turning off the room lights in the black-curtained test area, There is some beam decollimation but this effect was measured and found to be less than 0.5 degrees for a setup similar to the JPL LAPSS although an analysis shows that the decollimation should be about equal to that of the solar disc at Earth, 0.53 **degrees.**

Reduced Reading Size - As the incidence angle increases small Isc measurement error become magnified. Of particular interest is the rounding error since all readings are presented with only two decimal digit accuracy.

Assured Index of Refraction -As mentioned above, the coverglass front surface index of refraction used for all predicted values was set at 1.35 to obtain the best data fit, This best fit is somewhat qualitative, however it affects only absolute values not trends. Predicted curves for all cells used this value.

Random

A/D Count - The data acquisition system used on the LAPSS is typical in that it uses a digitized representation of the analog data which consists of whole counts, Rounding off to the nearest count is then a random error equal to +/-0.5 parts in 4096 or roughly +/-0.012%.

Temperature - Temperature measurements are displayed on the meter to the nearest tenth of a degree so the rounding of this value is a random error equal to +/-0.5 parts in about 280. Fortunately the Isc sensitivity to this error is about 0.0175°/ddegC for gallium arsenide cells and 0.0145%/degC for silicon cells so the overall temperature error effect of a +/-0.05 degree rounding error is +/-0.00875% for the test cells.

CONCLUSIONS

Using the combined cosine and Fresnel corrections gave very good predictions of the measured data when cells with filters which did not have an IR band-edge near the cell band-edge were involved.

Cells with blue-red and infrared reflection filters produced a noticeable deviation from predicted values.

At high incidence angles there is certainly performance greater than that predicted, but additional effort is required to fully understand this phenomenon,

IRR filters are available which do not show an angle of incidence effect. However, there is an absorptance penalty.

Irradiation of cells may slightly improve the angle of incidence related performance.

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REFERENCES

1. *Solar Cell Array Design Handbook,* Vol. 1, JPL Document #SP 43-38, Vol. 1, Jet Propulsion Laboratory, Pasadena, CA, Oct. 1976, pp 4.2-1 & -2 and 4.8-1 & -2.
2. Ross, R. G., Jr., et, al., "Measured Performance of Silicon Solar Cell Assemblies Designed for Use at High Solar Intensities," JPL Publication #TM 33-473 (N71-23780), March 15, 1971, pp 113-115.
3. Opjorden, R. W., "Solar Cell Optical Design Considerations," Conf. Rec. of 9th IEEE PVSC, Silver Springs, MD, May 241972, pp 164-173.
4. Wilson, A and Ross, R G., Jr., "Arigl@f-incidence Effects on Module Power and Energy Performance," Progress Report 21, April 1982 to January 1983, and Proc. of 21st PIM, JPL Doc. #5101-222, Jan. 1983, (NTIS, PC A22/MF AO1; 1), pp 423426.
5. Mueller, R. L., "he Large Area Pulsed Solar Simulator (LAPSS)," JPL Publication #93-22, Rev. A, July 15, 1994.
6. Heavens, O. S, "*Optical Properties of Thin Solid Films,*" Butterworths Scientific Publications, London, 1955, pp. 208-215.